Performance Coefficients and Flame Stability of Gas Appliance Burners

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Abstract

In order to appraise quantitatively the limits of satisfactory performance of practical gas appliance burners the use of a "performance coefficient" is proposed. The performance coefficient for a given burner may be determined by an indirect procedure. When the coefficient is subsequently combined with data derived from the flame stability diagram for any selected fuel gas, the limits of satisfactory performance of that burner when supplied with the fuel gas can be predicted. Experimental work indicates that the performance coefficient represents quantitatively the influence of burner design and construction alone on its performance and does not reflect the properties of the fuel. Examples of the utility of the performance coefficient in practice are given.

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The purpose of this investigation has been to study, in greater detail than has heretofore been done, the performance of domestic gas appliance burners. It was the immediate objective to relate more closely modern concepts of flame stability and the performance of contemporary appliance burners. As a result, it was believed, a quantitative measure might be devised which would characterize the influence of overall burner configuration on performance and distinguish these effects from those due to the nature of the fuel gas supplied. If such a measure can be determined it will immediately provide gas utility companies with a method for comparing the adaptability of the great variety of appliance burners in its community to changes in fuel gas supply and for estimating the restrictions placed on variations in fuel gas composition by burners "sensitive" to such changes.

A quantitative index related only to burner design and construction can serve as a sound basis for further study of individual elements, such as port depth, shape, slope, spacing, and disposition with respect to secondary air flow. Through such work it would be expected that significant improvement in burners could be more successfully achieved by appliance manufacturers.

In two previously published reports from this laboratory(6)(7) statements may be found of reasons for, and extent of, interest by the gas industry in a search for more fundamental methods than those now available for appraising burner and appliance performance. Experience and empirical tests have been the guide for estimating the permissible variations in fuel gas composition, which may occur when it is necessary to supplement or replace the supply of base gas in a community. In like manner, handbook recommendations(1) based on the results of empirical experiments have served to guide burner manufacturers. These methods of procedure provide at best only limited assistance for modern requirements.

The most significant limitations on the performance of an appliance burner are the conditions which result in the occurrence, on the one hand, of flashback, and on the other of blowoff. In gas industry practice the occurrence of luminous or yellow flames under certain conditions and of minute traces of carbon monoxide in the combustion products are also regarded as "unsatisfactory performance." However, this discussion will be limited to a consideration of flame stability.

The theory of flame stability limits proposed by Lewis and von Elbe,(4) and now widely accepted, may be applied here with some modifications to be developed. By this theory the limits of the stable flame regions may be expressed as "critical" values of the velocity gradient at the boundary of the stream of premixed fuel-air mixture issuing from the burner port. The boundary velocity gradient may be expressed as (6)(2)(3)

$$G = \frac{\lambda \bar{u}^2}{8\nu} \tag{1}$$

where λ is a friction or resistance coefficient relating the boundary velocity to the average flow velocity through the port, and is characteristic of the port geometry and the nature of the fluid flow. A flame stability diagram is a graph formed by plotting the critical values of G at the flame stability limits against the composition of the fuel-air mixture. The flame stability diagram is characteristic of the fuel alone. Thus the critical average flow velocity at the limits of the stable flame region is determined, for a given combustible mixture, by properties of the fuel gas represented by G, and of the burner port represented by λ.

The Performance Coefficient

The parameter λ, representing the influence of the burner port geometry, has been found to have the form

$$\lambda = a/Re^{b} \qquad (2)$$

for a variety of port geometries over a broad range of flow velocities expressed by the Reynold's number Re.[6] λ may be estimated theoretically for the simpler port forms, or determined experimentally from pressure drop measurements. An indirect method of determination has also[6][2][3] been suggested in which "critical" flow rates are measured with a fuel gas for which the flame stability diagram is known. Substituting the measured "critical" flow rate and the value of G appropriate to the fuel, and the fuel-air mixture composition used, in equation (1) the corresponding value of λ may be calculated. Experiments are made covering the range of Reynold's numbers of interest. Data presented by Grumer and associates[2][3] obtained in this manner with ports having circular and non-circular cross-sections compare favorably with values obtained by pressure drop measurements.

Consideration of the performance of multiple-port burners such as are found in many contemporary gas appliances indicates that their performance, with respect to the production of stable flames, may be somewhat different from that of an isolated individual port, or "monoport" burner.[6] The following differences may be pointed out:

1. The construction of atmospheric appliance burners is typified by those illustrated in Figure 1. Primary air is entrained in a Venturi throat by a jet of fuel gas. Some of the ports are nearer the point of attachment of the Venturi to the burner head than others, with the result that the rate of flow through the nearer ports is greater than that of the ports farther away. Blowoff may therefore occur first on the nearer ports while stable flames still exist on the others.

2. The spacing of the ports may influence "piloting" from one flame to another. The proximity of one port to another, often resulting in coalescence of flames, improves stability toward blowoff and may be desirable.

3. Spacing and burner configuration as a whole influences the disposal of combustion products from the vicinity of the flames and the pattern of secondary air flow. For example, with the burner illustrated in Figure 1(a), the accumulation of combustion products and deficiency of secondary air near the flames of the internal circle of ports permits these flames to blow off more readily than those of the external circle.

4. With square edged ports an incipient detachment of flame occurs at smaller flow rates than does the final blowoff. The latter only, however, is observed with tubular burners and with single cylindrical ports with rounded entrances and is the quantity expressed in flame stability diagrams. In gas industry practice a conservative definition of the limit of "satisfactory performance" is that flow at which the first incipient detachment is observed on any port of the multiple port burner. This will be termed "initial lifting" in this discussion.

5. Any irregularities of a selected burner attributable to commercial production methods. These include the occurrence of burrs, irregular port formation, etc. In this group may also be included any deliberate differences in port size in one burner. In this case the larger ports will more strongly influence the occurrence of flashback while the smaller ports will be more "sensitive" to blowoff.

In order to embrace quantitatively in one parameter characteristic of the multiple port burner, the influence of all these items, as well as that of the resistance coefficient λ, a "performance coefficient," P_λ is proposed. Experimental study should show whether or not this parameter is related to the burner design and construction alone, as the resistance coefficient λ reflects the port geometry. P_λ for a selected burner may be determined by the indirect procedure described, and calculated by an expression similar to equation (1)

$$G = \frac{P_\lambda \bar{u}^2}{8\nu} \qquad (3)$$

G is the critical boundary velocity gradient for the stability limit observed, at the pertinent fuel-air ratio, and is obtained from the flame stability diagram for the fuel used. $\bar{u}$ is the average linear rate of flow through all the ports, calculated from the volumetric rate of flow to the burner and the total port area, $\bar{u} = \frac{V}{A}$.

The experiments will provide sufficient data to estimate the relationship between P_λ and the Reynold's number Re. Moreover, if the performance coefficient is characteristic of the burner construction alone data obtained with two or more fuel gases should fall on the same curve when P_λ is plotted against Re.

The plan of the experimental work then was to determine P_λ as described for several selected multiple port contemporary gas appliance burners. More than one fuel gas was used with each burner, and a broad range of variation of Re was sought by using fuels having as different flame stability characteristics as practicable. The relation of P_λ to the Reynold's number was determined for each burner, for both the flashback and the lifting limits.

Apparatus and Procedure

Four appliance burners were selected for the experiments, illustrated in Figure 1. Two burner heads were available for the interchangeable-head burner, (d) and (e), and two sets of observations were made, one with each head. The geometric characteristics of the burners and ports are listed in Table I.

More than one fuel gas was used for tests with each burner, selected so that the desired range of variation of Reynold's number could most readily be attained. For the most part natural gas, cylinder methane, or propane were used for blowoff determinations. However, flashback could usually be obtained only with mixtures of a hydrocarbon gas and some hydrogen. These mixtures were prepared in the laboratory by mixing, under pressure, the individual constituents in a compressed gas cylinder.

With predetermined rates of fuel flow to the burner, measured by a calibrated differential orifice flowmeter, sufficient primary air was premixed with the fuel (the air-shutter of the burner being completely closed) to produce either initial lifting or flashback, as desired. The composition of the fuel-air mixture, at the critical limit, was determined by drawing a sample from the burner head through a Pauling oxygen analyzer. From the observed oxygen content, the percent air and the percent fuel in the combustible mixture were calculated.

TABLE I

Geometric Characteristics of Ports on Appliance Burners

Burner (Figure 1)	No. Ports	Shape	Depth cm	Port Dimensions cm	Total Area cm	Distance between Centers cm
a	40	Round	0.53	0.2794 (diameter)	2.4516	0.731
b	56	Round	0.45	0.2818 - 0.2946 (diameter)	3.5436	0.694
c	68	Round	1.17	0.2705 (diameter)	3.9079	0.616
Interchangeable head (d)	44	Square	0.80	40 - 0.257 side 4 - 0.230 side	2.8711	0.499 1.995
Interchangeable head (e)	26	22 - rectangular 4 - T-shaped	0.80	22 - 0.635 x 0.237 4 - irregular	3.7744	0.907

The value of P_λ for the limiting conditions in each test was calculated by equation (3). The required values of G were found from flame stability diagrams prepared for each fuel gas. These diagrams were determined experimentally with tubular burners, or with short cylindrical ports with rounded entrances in the manner described by Wilson and Hawkins.[7] Kinematic viscosities of the combustible mixtures were estimated by the method of Wilke.[5]

Experimental data obtained with each burner were plotted graphically to show the relation between P_λ and Re. It was found that the data could be represented satisfactorily by curves of the form

$$P_\lambda = a/Re^b \tag{4}$$

The constants pertaining to each burner were evaluated by the method of least squares.*

Experimental Results

Data obtained with the star-shaped burner, Figure 1(b), have been plotted in Figure 2 for purposes of illustration. Individual data points represent performance coefficients, calculated with equation (3), and the corresponding Reynold's number at the critical flow rates for initial lifting and for flashback. It is observed first that the data representing the two stability limits are clearly separated and distinct. In fact, at a given Reynold's number, performance coefficients for initial lifting and for flashback are an order of magnitude different.

It is reassuring to find that, using consistent criteria for each limit, data obtained with different fuel gases fall on the same curves. These observations support the hypothesis that the performance coefficients obtained in the manner described are parameters characteristic of the burner construction, and are not influenced by the type of fuel gas supplied or the proportions of air and fuel in the combustible mixture.

Similar experimental data were obtained with the other burners illustrated, including the two heads, (d) and (e), of the interchangeable-head burner. At least two different fuel gases were used with each burner. The results of all experiments are summarized in Figures 3 and 4 (data points have been omitted for clarity). Figure 3 represents initial lifting of flames, and Figure 4, flashback. It was found that the data for each burner could be represented by a curve of the form of equation (4), and that the agreement between the data points and the calculated curves was at least equal to that illustrated by Figure 2 in all cases. Values of the constants a and b of equation (4) pertaining to each burner are listed in Table II. The coordinate scales of the two graphs again indicate the disparity of an order of magnitude between corresponding flashback and initial lifting curves for all burners.

Discussion

In addition to the conclusion that the performance coefficients thus determined are characteristic parameters related to the burner construction, three other features of the graphs, Figures 3 and 4, will bear discussion.

First, the published results[6][2] of experiments with individual burner ports give no clue that separate curves should be obtained representing flashback and blowoff. However, there is a small difference in flow between initial lifting and complete blowoff with square-edged ports.[2] Thus for an individual port the curve

*To calculate Reynold's numbers applying to burner ports other than circular the "hydraulic radius" of the port cross-section is used.

TABLE II

Constants for Equations for Performance Coefficients of Appliance Burners

$$P_{\lambda} = a/Re^{b}$$

Burner (Figure 1)	Flashback		Lifting	
	a	b	a	b
a	104	1.316	88	0.865
b	503	1.669	477	1.204
c	157	1.363	150	0.980
d	436	1.680	102	0.989
e	335	1.590	19	0.766

representing the relation between λ and Re at <u>initial lifting</u> would fall above that for blowoff by a small margin, since lifting occurs at smaller flow rates. Since the port resistance is embraced by P_λ, this difference will appear in the present data, but it is not of sufficient magnitude to account for the separation of the curves in Figure 2, or between corresponding curves in Figures 3 and 4. It seems likely that a portion of the observed spread between the lifting and flashback curves may be attributed to other differences itemized above between individual ports and multiple port appliance burners. Only item 2, "piloting" between neighboring flames or coalescence of flames, might be expected to increase the stability toward lifting and thus decrease the spread between the curves.

In the second place, comparison with data on individual ports, obtained by either direct measurement of pressure drop or by the indirect method, reveals a difference in slope between the curves reported for λ and those found in this study for P_λ. Again the discrepancy can only be attributed to the other performance characteristics of appliance burners noted.

Finally, differences between corresponding curves for the drilled port burners, Figure 1(a), (b) and (c), require explanation. Differences in port depth may account for them in part. However, the limited published data do not suggest a change in slope with a difference in port depth but only a parallel displacement of the curves. The data for individual ports of Grumer <u>et al</u>[2][3] indicate different slopes of curves for λ <u>vs</u> Re for channels having square, rectangular, and triangular cross-sections. Detailed comparison with the present results is, however, not possible because of the length of the "tubes" which Grumer used.

These experiments therefore do not explain quantitatively the influence of each feature of burner design and construction on the limits of satisfactory performance. It is believed, however, that a sound basis has been provided for further study of these elements, which will lead to a clearer understanding of the relative magnitude of their influence and of their importance.

Practical Application of Performance Coefficients

Practical use can be made of the performance coefficients determined for any burner by combining such data with flame stability data for any selected fuel gas. This may be illustrated by calculating performance curves which may be interpreted to show the behavior of a burner when supplied with a selected fuel and its relation to the heat input and air shutter adjustment. These curves have been familiar to the gas industry for many years,(1) although it has heretofore been necessary to obtain them by direct experiment. This fact has limited their utility to those fuel gases which have actually been available in the laboratory. Since flame stability diagrams may now be derived for fuel gases having nearly any assumed chemical composition,(3) the ability to estimate burner performance with different fuels is greatly extended.

In order to calculate data from which performance curves for a burner, such as that illustrated in Figure 1(a), may be plotted, the value for P_λ, the performance coefficient of the burner, in equation (4) may be substituted into equation (3), and since

$$\mathrm{Re} = \frac{D\bar{u}}{\nu} \tag{5}$$

it is found that

$$G = \frac{a\nu}{8D^2} \cdot \mathrm{Re}^{(2-b)} \tag{6}$$

or in a form more convenient for calculation

$$\log \mathrm{Re} = \frac{1}{2-b} \log \left(\frac{8D^2G}{a\nu}\right) \tag{6a}$$

To calculate the lifting curve for a burner, the value of the constant, a, and the exponent, b, of the equation for its performance coefficient curve for lifting are used. At a series of fuel-air ratios, for which values of the critical gradient at blowoff are obtained from the flame stability diagram for the fuel gas selected, the Reynold's number corresponding to the critical flow rates are calculated with equation (6) or (6a). Since the linear and volumetric flow rates are related by

$$\bar{u} = \frac{V}{A} \tag{7}$$

the critical flow rate at lifting may be obtained from the critical Reynold's number by

$$Re = \frac{DV}{A\nu} \tag{8}$$

Having the critical total flow at lifting and the percent fuel in the combustible mixture the corresponding fuel rate and heat input to the burner may be readily found. The curve for flashback is calculated in the same manner using the equation for the flashback performance coefficient, and critical gradients at flashback from the flame stability diagram of the fuel.

These calculations have been made for an example in which it is assumed that a manufactured oil gas is to be supplied to an appliance burner such as that in Figure 1(a). The assumed composition of the fuel is

Inerts (CO_2, O_2, N_2)	4.9%
Hydrogen, H_2	21.2
Carbon monoxide, CO	1.1
Paraffins	46.9
Olefines	25.9
	100.0%

Heating value (gross)	1076 Btu/cubic foot
Specific gravity (air = 1.0)	0.659
Stoichiometric air	9.706 cubic feet air/cubic foot gas

The performance curves for this burner and fuel combination are then those of Figure 6, when the rate of heat input to the burner is plotted against the percent of the stoichiometric proportion of air entrained as primary air. The breadth of the stable flame region, with respect to heat input rate and aeration, is represented by the space between the flashback and blowoff curves.

Similar calculated curves are shown in Figure 7 to illustrate the behavior of burner Figure 1(e), when supplied with propane.* The experimental points indicated were obtained by another observer in an independent study. The intersection of the flashback and lifting curves clarifies the original puzzling observation that only flashback was observed between 4000 and 11,000 Btu per hour input when the primary aeration was between 110 and 85% of stoichiometric air. The lifting curve falls within the flashback region, and under these conditions flame will propagate back through the ports. The observed and calculated flashback curves appear to be in very satisfactory agreement.

Satisfactory and complete application of performance coefficients to the design of new burners must await further study. At present, data available can be used within limits for approximations. Averages of the curves found in Figures 3 and 4 may be used if the proposed burner port sizes and shapes to not deviate too widely from those now used in practice. The effect of port size

*The curves will be the same whether the fuel is pure propane or a propane-air mixture. The location of a point on the diagram, a "performance point," representing a particular orifice and air shutter adjustment will depend on the proportions of air and propane in any mixture supplied.

enters directly through equation 6 and 6(a). However, the effect of port depth, spacing, attitude toward the vertical, and the burner configuration with respect to the relative location of ports and Venturi can be appraised only qualitatively. It appears that these factors may be reflected in the slope of the performance factor curves, and in the spread between the flashback and lifting curves. The greatest burner "flexibility," represented by the widest attainable spread between flashback and lifting curves, as plotted in Figure 6, will be attained by burner designs for which the two performance coefficient curves are brought closest together.

Summary

1. A "performance coefficient" is developed as a parameter for appraising the influence of burner design and construction on the performance of practical gas appliance burners.

2. The "performance coefficient" includes the resistance coefficient of the ports, and other elements of the burner as a whole, as an overall coefficient.

3. It is demonstrated that the "performance coefficient" for any selected burner can be determined indirectly through the use of a fuel gas for which the flame stability limits are known. The operation of the burner when supplied with any other fuel gas may then be predicted.

4. A procedure for estimating performance curves for any burner and fuel combination is described and illustrations given.

5. Avenues for further study are indicated, through which the influence of individual elements of burner design may be determined in greater detail. These elements are port depth, spacing, and burner configuration with respect to the location of the Venturi.

Nomenclature

A = total area of ports.

D = diameter of port.

G = boundary velocity gradient.

P_λ = performance coefficient of appliance burner.

R_H = hydraulic radius of port = $\frac{\text{port area}}{\text{perimeter}}$.

Re = Reynold's number.

V = volumetric rate of flow through port.

a and b = parameters relating performance coefficients and Reynold's numbers.

r = radius of port.

$\bar{u}$ = average linear velocity through port = $\frac{V}{A}$.

λ = resistance coefficient.

ν = kinematic viscosity of the air-fuel mixture.

F = Fraction of stoichiometric fuel in combustible mixture

$$\left(= \frac{\text{percent fuel in mixture}}{\text{percent fuel in a stoichiometric mixture}} \right)$$

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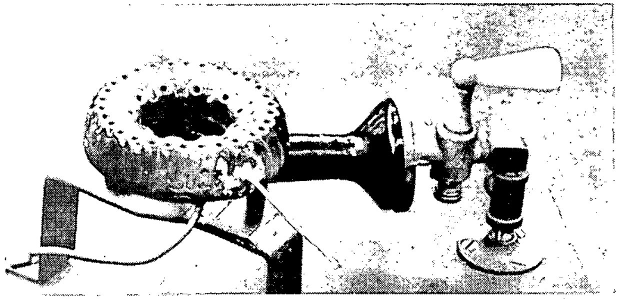
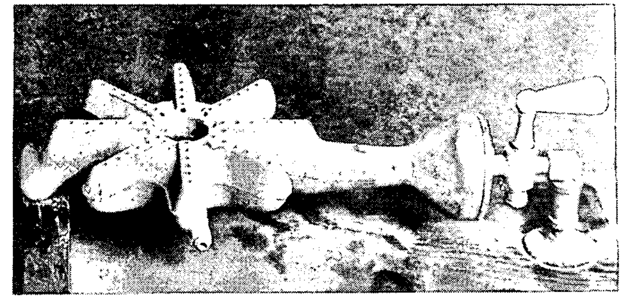
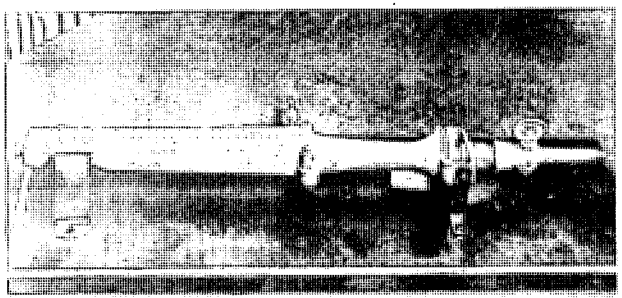


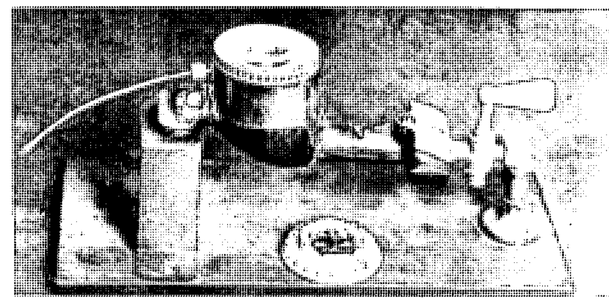
(a)



(b)



(c)



(d) (e)

Figure 1 - Gas Appliance Burners.

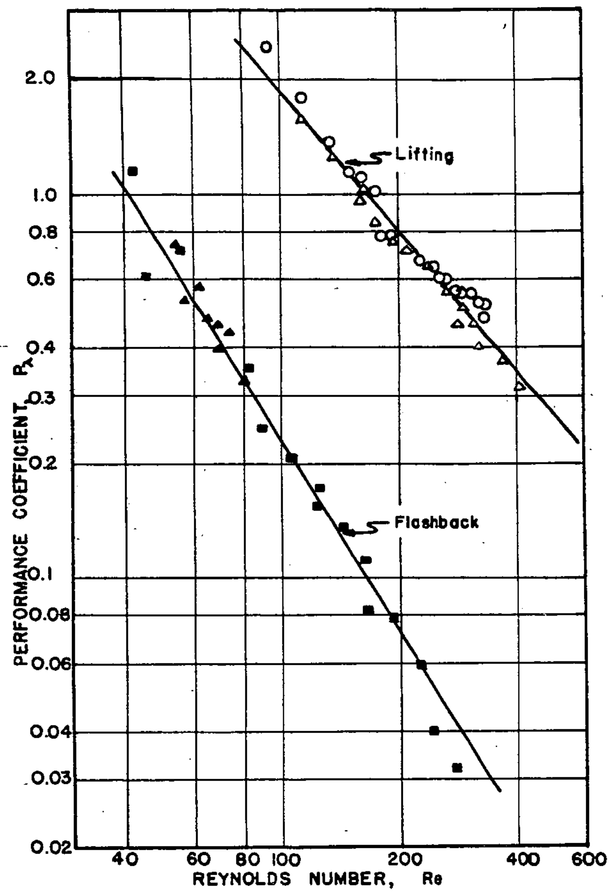


Figure 2 - Performance Coefficients, Star-shaped Burner (b).
O Natural Gas; ▲, △ 75.3% methane + 24.7% hydrogen;
■ 65.8% methane + 34.2% hydrogen.

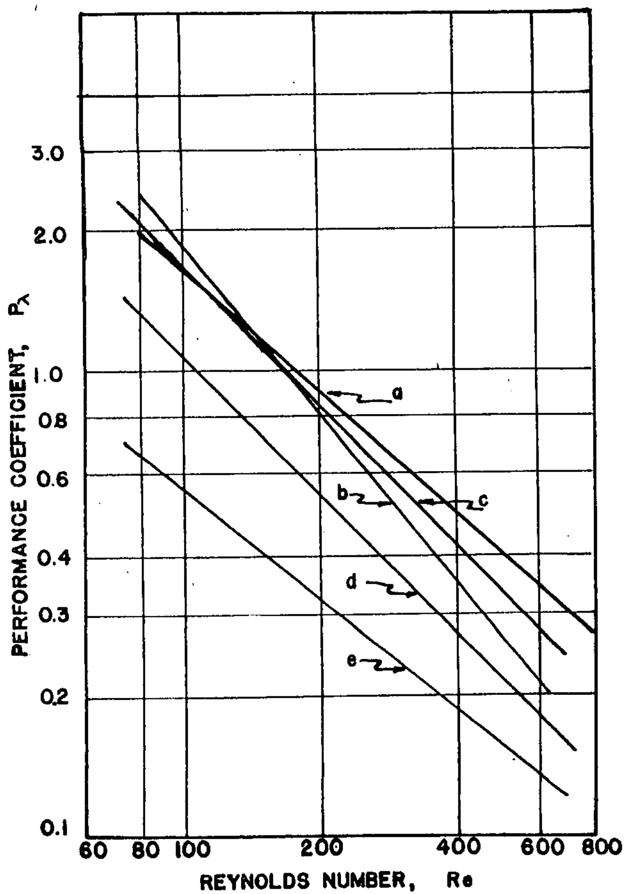


Figure 3 - Performance Coefficients, Appliance Burners. Initial Lifting.

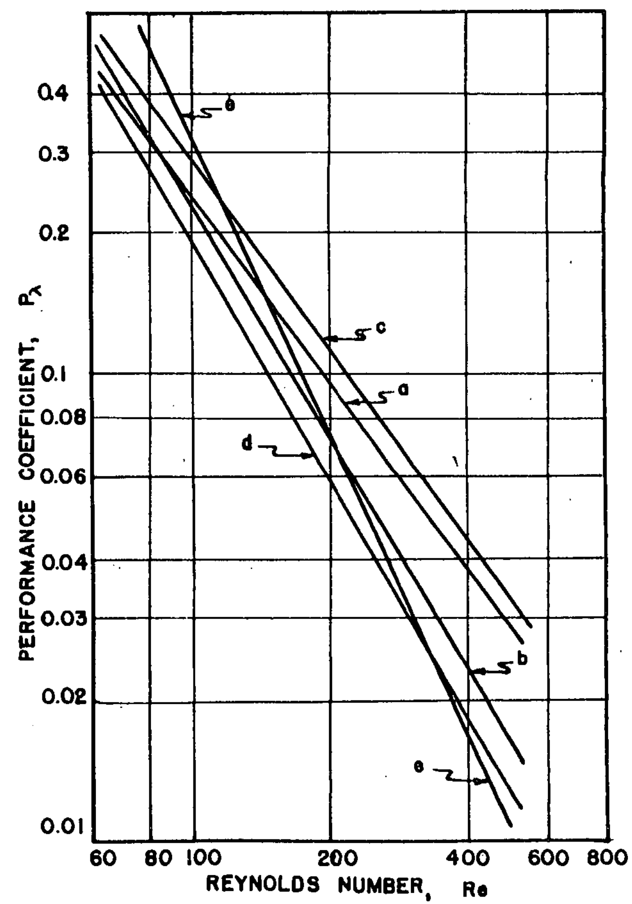


Figure 4 - Performance Coefficients, Appliance Burners. Flashback.

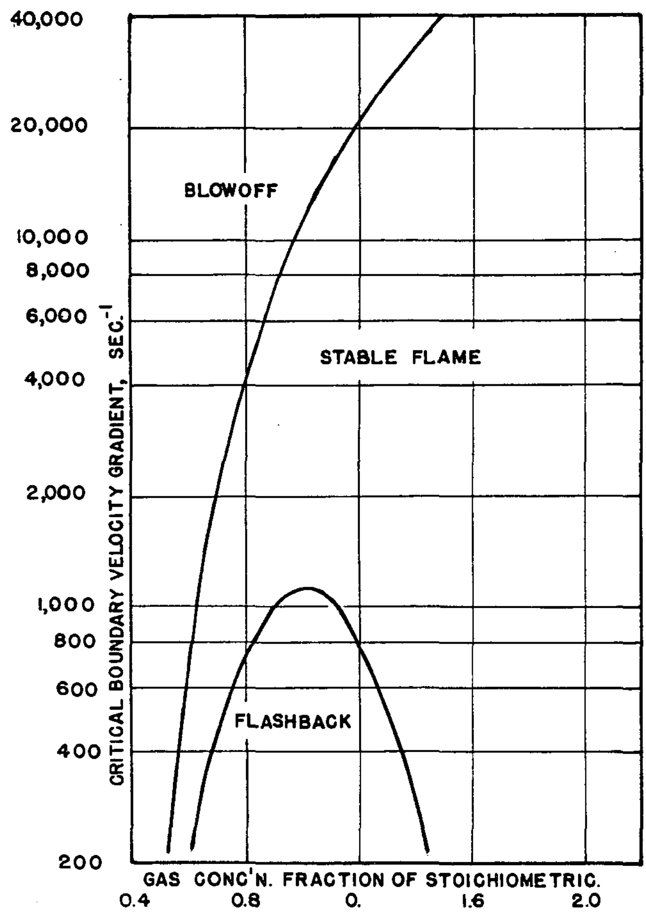


Figure 5 - Calculated Flame Stability Diagram, Manufactured Oil Gas.

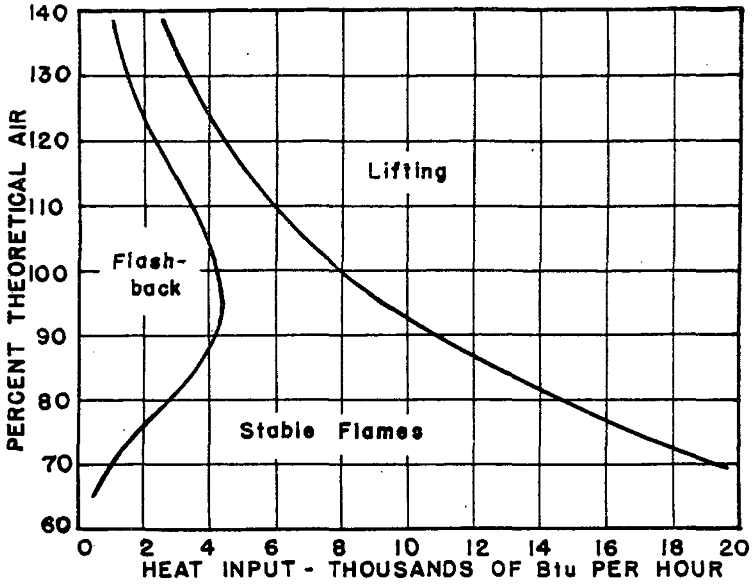


Figure 6 - Calculated Performance Curves, Burner (a) with Manufactured Oil Gas.

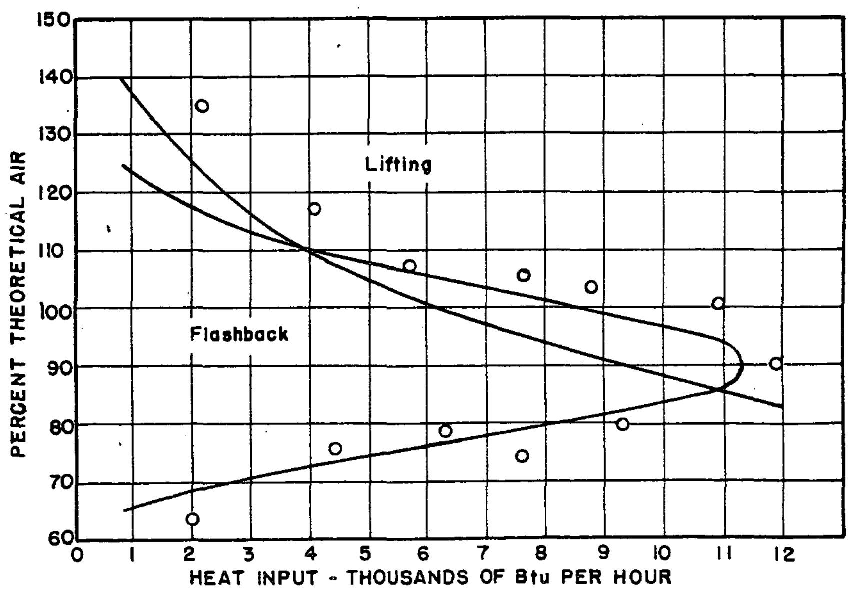


Figure 7 - Calculated Performance Curves, Burner (e) (Natural gas head) with Propane.